HYDROLOGY AND PERMAFROST

BY

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Introductory Session

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Abstract

This paper presents summary information of the water balance in northern North America, and introduces characteristic features of hydrology in northern regions.

The terrestrial portion of the hydrological cycle in country underlain by permafrost possesses several peculiarities that are conditioned by ground thermal conditions. The chief contributions to runoff occur from seasonal rainfall and snowmelt by direct surface flow, or by interflow through the active layer: permafrost restricts exchanges between surface water and deep groundwater. Four runoff regimes typical of northern rivers (subarctic nival, arctic nival, muskeg, proglacial) are illustrated.

Permafrost presents an impermeable stratum near the surface. However, it is perforated to a greater or lesser extent where it is discontinuous, where taliks occur, and below sufficiently large water bodies. These features mediate groundwater occurrence. Standing water in lakes and in muskeg may be retained by frost phenomena: some morphological features of northern lakes and bogs derive from this effect. Seasonal freezeback may trap water under pressure in unfrozen sediments, which may lead to "icing".

System models for hydrological investigations are introduced, which emphasize special features of water occurrence in northern regions.

Résumé

Le présent document donne un bref aperçu de l'équilibre hydrologique en Amérique du Nord et expose des phénomènes caractéristiques de l'hydrologie dans les régions du Nord.

La partie terrestre du cycle hydrologique dans les régions de pergélisol présente plusieurs particuliarités qui dépendent des conditions thermales souterraines. Les principales causes de ruissellement sont la fonte de la neige et les pluies saisonnières qui entraînent un écoulement superficiel direct ou hypodermique dans la couche active et quant au pergélisol, il diminue les échanges entre les eaux superficielles et souterraines. On décrit également quatre régimes d'écoulement typiques des rivières du Nord, soit les régimes nival subarctique, nival arctique, de muskeg et pro-glaciaire.

Près de la surface, la couche du pergélisol est imperméable. Elle est toutefois plus ou moins perforée aux endroits discontinus où se trouvent les ilôts gelés et au-dessous des nappes d'eau suffisamment grandes. Ces éléments interviennent dans la formation des eaux souterraines. Les eaux stagnantes des lacs et des muskegs peuvent être retenues à cause du gel, et certaines caractéristiques des lacs et des marais du Nord en résultent. Le regel saisonnier peut emprisonner l'eau sous pression dans des sédiments non gelés, pouvant entraîner glaciation.

On présente les modèles de régimes concernant les recherches hydrologiques, modèles qui mettent l'accent sur les caractéristiques spéciales de la formation de l'eau dans les régions du Nord.

Hydrology and Permafrost
with Reference to Northern North America

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Introduction

Until recently, knowledge of the hydrology of northern North America remained very rudimentary. This circumstance was sustained by the inaccessability of the region and the difficulty of maintaining routine hydrometeorological measurement programmes through northern winters. Since about 1965, the imminence of large scale resource developments in the north, increased concern to develop an adequate inventory of the total water resource of North America, and an increased tempo of academic research have conspired to extend the scope of investigations. The last decade has seen the appearance of virtually all quantitative information about the terrestrial phase of the hydrological cycle. Detailed studies of water - frozen ground interactions have, however, only begun during the last two or three years. A bibliographic summary of hydrological work in arctic and subarctic regions to 1972 is provided by Dingman (1973a).

This paper presents a summary of knowledge about the water balance in northern North America, and introduces characteristic features of hydrology in northern regions as a preface to the more detailed discussions which follow. For the present purpose, "northern North America" is taken to be that part of the continent where permafrost may be found, either continuously or discontinuously, at low elevations (hence excluding isolated high areas in the Western Cordillera where perenially frozen ground occurs: cf. fig. 1).

The Water Balance

Summaries of the major components of the water balance over northern North America are given in figures 2 - 4. Precipitation records remain representative only of lowland areas, there being no regular stations at high elevation anywhere in the region. Furthermore, following their critical examination of component fields of the water balance, Hare and Hay (1971) concluded that inconsistencies in the results probably stemmed largely from systematic undermeasurement of precipitation. The negative bias present in precipitation measurements is well known: pertinent confirmation of the effect in the north has been provided by Cook (1960)

precipitation occur as snow (cf. fig. 2), but the effect of snow storage is nevertheless the single most important feature of the hydrological cycle everywhere in the north.

The presence of permafrost restricts exchanges between surface and groundwater. A "perched" water table frequently occurs in the active layer above the frost table and standing water on the surface is a frequent result of frost barriers. The chief contributions to runoff are from seasonal rainfall and snowmelt by direct surface flow or by flow through the active layer. Contributions from deep groundwater circulation are often minimal in areas of substantially continuous permafrost and here runoff can be analyzed as a surface/soil flow phenomenon.

Lake Types

Lakes and Bogs

Despite their myriad numbers in some areas, lakes are a little-studied element of northern hydrology. Five major types of lake may be distinguished:

(1) Thaw Lakes:

These lakes occur where permafrost degradation in ground with a high ice content has caused settlement of the surface sufficient to hold a standing water body, or where terrain and frost table configuration have produced an interior drainage basin. Once established, the lake itself alters the local thermal regimen, so that further thermal erosion may be prompted. A thaw lake may remain very shallow, freezing to the bottom each winter, so that permafrost persists very near the lake bed. If, however, the lake becomes sufficiently deep that it does not freeze to the bottom in each year, then the additional heat reservoir represented by the unfrozen water through the winter will initiate further degradation of permafrost (cf. Black, 1969). Since many of the lakes have no external drainage, their water balance is determined by the balance of inflow and evaporation during the summer months. The inflows are often not channelized. Some lakes have only very sporadic outflows.

Thaw lakes occur in several special forms, including the "oriented lakes" of the arctic coast, and deep, linear ponds in areas of ice wedge melting--often along small streams.

(2) Kettle Lakes:

Kettle lakes are common in pitted outwash. They are hollows left after ice melted out of glacial outwash deposits. Some have subsequently developed farther due to thaw processes. The lakes are irregularly

precipitation [illegible] (cf. Fig. 2), and the effect of snow storage [illegible] the single most important [illegible] of the hydrological [illegible] in the Arctic.

The presence of permafrost restricts [illegible] between surface and ground water. [illegible] occurs in the [illegible] and [illegible] in the surface. [illegible] The other contributions to runoff are [illegible] by direct surface flow or by [illegible] the active layer. Contributions from deep groundwater [illegible] of [illegible] permafrost and [illegible] as a [illegible] flow [illegible].

Lakes and Ponds

Despite the [illegible] [illegible] of surface water [illegible]. [illegible] types of lake may be distinguished:

(1) Thaw lakes

Thaw lakes occur where permafrost degradation [illegible] with the [illegible] of the surface sufficient to hold a standing water body, or where terrain and [illegible] have produced an impounded drainage [illegible]. Once established, the lake itself alters the local thermal regime, so that further [illegible] may be promoted. A lake [illegible] the bottom [illegible], so that permafrost [illegible] with [illegible] the lake bed-[illegible]. If, however, the lake becomes sufficiently deep that it does not freeze to the bottom in each year, then the [illegible] underlain by a talik [illegible] of the [illegible] water through the [illegible] will indicate [illegible] of permafrost (cf. Black, 1969). Since many of the lakes have no external drainage, their water balance is determined by the balance of inflow and evaporation during the summer months. [illegible] are given for [illegible] lakes have only [illegible].

Thaw lakes occur in several [illegible] of the [illegible], and [illegible] in areas of [illegible] along small streams.

(2) Arctic lakes

Arctic lakes are [illegible] in glacial [illegible]. They are [illegible] of [illegible] origin [illegible]. [illegible] are irregular.

shaped and usually fairly deep. Again, many have interior change.

(3) Lakes Dammed by Glacial Deposits:

These lakes are relatively few in number but are usually large, and include most of the sizeable lakes found in mountain valleys. Lakes in former glacial meltwater channels are common. The hydrology of these lakes is not in principle different from that of lakes in more southerly regions.

(4) Lakes in Structural Depressions:

These lakes are similar to the last ones, but their location is determined by bedrock geology.

(5) Delta Lakes:

The large arctic coast river deltas (notably Mackenzie delta, Colville delta) contain many lakes in interchannel areas. These develop readily on the outer portions of the deltas and are maintained as levee building and channel stabilization occur. Many remain connected to channels, and direction of drainage (into or out of the lake) varies with river channel-stage. Mackay (1963) has given the most detailed discussion of these lakes.

Little work has been done on the hydrology of arctic and subarctic lakes. Hartman and Carlson (1973) have studied a small lake near Fairbanks that was isolated by permafrost from the subpermafrost groundwater system. Kane and Slaughter (1973) studied another lake in the region that gave evidence of recharge from groundwater, and postulated that many of the lakes in the Yukon-Tanana lowlands are so connected.

Bogs and marshes are widespread in the arctic and subarctic as water is constrained to remain near the surface by the presence of permafrost below. Bogs have been described by Drury (1956) and Allington (1961), amongst others, and considerable botanical work has been carried out. However, almost no hydrological work has been done beyond that of Brown et al (1968) on runoff. Thom (1972) has indicated that runoff conditions during spring melt may be responsible for initiating the singular patterns of string bogs. Considerable practical experience has been gained in managing muskeg areas in the subarctic (cf. MacFarlane, 1969).

Runoff

Surface flow of water--particularly of snow meltwater below snow banks--is common in arctic and subarctic regions. Continuous ground cover of moss and lichen or of tundra grasses, sometimes abetted by frozen ground, effectively prevents erosion and rill development, however,

so that overflow of puddles and ponds, or seepage through the sodmat, is the usual means of water movement (cf. Dingman, 1973b). On bare ground in the high arctic, rillwork and gullying may appear, though, as the result of erosional activity by summer rains (Rudberg, 1963). Often, combined water and solifluction activity occurs to form drainage lines on hillsides, though no conventional stream channel appears. Such drainage lines often remain wet throughout the summer and vegetation may effectively form sills and dams behind which standing water persists.

Regime types for northern rivers can be classified by source and timing of runoff (fig. 5). The latter characteristic is influenced to a greater or lesser extent by frost phenomena. Watershed size has some special, frost-related consequences in the north as well.

(1) Subarctic, nival regime:

Runoff is characterized by a snowmelt flood in spring and generally low levels of flow throughout the summer, punctuated by periodic rainstorm floods. Such floods may be more severe than the spring freshet, especially for rivers with headwaters in mountainous regions where heavy summer rainfalls may be orographically enhanced and snowmelt may still continue (cf. MacKay et al, 1973).

(a) winter dry: The entire watershed freezes so that flow cannot be maintained throughout the winter. The effect is observed on larger rivers farther to the north.

(b) perennial flow: Large subarctic rivers may continue to flow at very low level right through the winter, under ice cover, as groundwater seepage continues. Much of the base flow is derived from unfrozen gravels along the river channels, though deep springs occur in the Cordilleran zone. This regime type is particularly characteristic of northward flowing rivers whose headwaters may lie in discontinuous permafrost areas to the south. These rivers may experience ice jams during spring breakup, which may precede peak nival runoff, so that an early high water period may occur that is associated with ice dams (cf. Bolsenga, 1968, for review of literature).

(2) Arctic, nival regime:

In regions of continuous permafrost there is little possibility of groundwater continuing to provide a base flow in winter except in remarkable circumstances. Taliks may exist under the frozen channel bed (cf. Brewer, 1958, Waller, 1966; Williams, 1970a; Sherman, 1973), otherwise permafrost occurs under the river at shallow depth. The spring snowmelt flood is apt to be the most severe one, for generally lighter

peak intensities and smaller total volumes of rainfall are usual in the arctic, by comparison with subarctic regions. This may not be true of very small watersheds, however, where locally intense rain may produce major floods. Pissart (1967) has provided a description of the regime of high arctic rivers.

(3) Proglacial regime:

Such rivers in arctic regions, like those farther south, do not experience so abrupt a spring freshet. Discharge continues to rise until late summer as progressively higher zones on the glacier experience melt and become effectively contributing portions of the watershed.

(4) Muskeg regime:

Muskeg is intimately associated with poor drainage and its presence enhances it. Because of the large water retaining capacity of muskeg vegetation, and high resistance to runoff presented by the vegetation and frequently irregular surface, flood flows are greatly attenuated in watersheds dominated by it. Similar hydrological response is often associated with grassy or heathy tundra where, again, thick sodmats and hummocky surface may present high water absorbing capacity and high resistance to flow. The effect is similar to that of the presence of a relatively large lake. Lowland tundra with many standing water bodies also exhibits a much attenuated flow regime.

The response of watersheds to individual input events is also affected by the presence of permafrost. The most detailed study has been made by Dingman (1971, 1973b) for a small watershed of 1.8 km^2 area with discontinuous permafrost under black spruce-moss and white spruce-birch woodland, near Fairbanks, Alaska. His findings may be summarized as follows:

- response time varied from 0 to 13 hours, but was not systematically related to antecedent moisture conditions in the watershed;
- streamflow recession was approximately exponential, with a decay constant, t^*, averaging 39 hours, though the range was from 20 to 80 hours;
- variation of t^* may at least in part be explained by varying rates of evaporation on the watershed.

The recession time is very large by comparison with comparative data in temperate regions.

Table 3 presents more or less comparable data from other studies, as deduced from storm hydrographs. In general, response times are relatively short, especially for high arctic and proglacial watersheds.

There seems to be two reasons for this:

1) Presence of permafrost at shallow depth inhibits deep infiltration of water and encourages immediate runoff of a high proportion of input water once the active layer is wetted;
2) relatively sparse vegetative cover reduces resistance to surface flow.

Glacierized watersheds represent extremes in both respects. An exception to this behaviour is represented by Ogotoruk Creek, Alaska, with a response time of about 20 hours (Likes, 1966). This watershed is covered by the thick sodmats of a series of Eriophorum-Carex communities and is typical of large areas of low Arctic tundra. The high water retaining capacity of the sodmat conditions the very slow response. The magnitude of the response of Ogotoruk Creek was varied for moderate rainfall inputs indicating the importance of antecedent moisture conditions in determining storm runoff: however, for large inputs, the magnitude of the response became essentially linear. Dingman (1973b) has schematized this pattern of storm response in terms of a variable source area for storm runoff, which depends on the proportion of the watershed saturated before the storm begins. This picture is consistent with the appearance that overspill from puddles and ponds is the chief mechanism for surface (storm) runoff.

The characteristics of recessions are difficult to generalize, since data are sparse, and are not all determined on a uniform basis (cf. Table 3). It does appear possible to discriminate two sets of circumstances. High arctic and proglacial watersheds have relatively short recession periods for reasons similar to those which determine their rapid response: there are relatively few reservoirs where water may be held for extended periods of time. Watersheds with good vegetation cover (cf. Ogotoruk Creek, Glenn Creek) exhibit long recessions. The extreme in this respect is represented by flat, marshy watersheds with extensive standing water on the surface. Brown et al (1968) studied one such watershed (area 1.6 km^2) at Barrow, Alaska, where the recession period was of order 100 hours.

Groundwater

Literature on groundwater in permafrost regions has been exhaustively reviewed by Williams (1965), and Williams and van Everdingen (1973) have recently provided an authoritative review of current work. In addition, several papers in the present symposium treat aspects of groundwater

occurrence, so that this section will be restricted to introductory concepts.

The occurrence of groundwater in permafrost regions is not essentially different from groundwater occurrence in general. However, the introduction of permafrost causes several important modifications in groundwater hydrology which may be summarized as follows:

- in frozen areas the water is rendered immobile as ice;
- the characteristic low temperature of water in permafrost regions reduces the rate of groundwater circulation by raising the viscosity of the water (by a factor of 1.2 - 1.8 over usual conditions in temperate regions);
- permafrost may be viewed as an effectively impermeable structure (but cf. Williams and van Everdingen, 1973), and so introduction of permafrost essentially raises the number of barriers to groundwater flow. In particular, groundwater movements are often constrained to corresponding surface water catchments, since surface drainage divides are frequently permafrost high points;
- permafrost may alter the water table radically: perched water tables are common where permafrost "dams" may induce radical departures from the normal configuration of the water table as determined by structure and surface relief.

A widely accepted classification for groundwater in permafrost regions is that of Tolstikhin (1940), which is given in Table 4.

Suprapermafrost water occurs on top of the permafrost, often saturating the ground. Sources for the water include meltwater, rain, seepages of surface water, and condensation from humid air. This water freezes annually (unless an unfrozen layer persists between the seasonal and perrennial frost).

Intrapermafrost water occurs in "talik" zones within the frost zone. Such water may be replenished by infiltration from above or below the frost, and, loosely interpreted, may be taken to include water which occurs in any situation within the permafrost zone where, for some reason, frost is absent. Such areas are most common along river beds and banks and around lakes, where extensive thawed areas are supported under the water body (cf. Lachenbruch et. al., 1962; Gold and Lachenbruch, 1973). Toward the southern margins of the region of permafrost the occurrence of "windows" right through the frost zone is common so that circulation can occur between supra- and subpermafrost waters. Under major rivers and lakes such zones occur well into the continuous permafrost regions.

Subpermafrost water may be aquiferous, artesian, or fissure water, and exists much as elsewhere, though overlying permafrost may modify its occurrence somewhat.

The occurrence of groundwater is associated with river flow in two ways. First, it leads to the possibility for continued recession flow throughout the winter where permafrost windows or unfrozen channel beds exist.

Secondly, where springs or seepages occur, massive accretions of ice may develop in winter. Icing or aufeis (Russian: naled) (cf. Carey, 1970) appears to be of two types:

1) Riverbed Seepages: In the autumn, groundwater seepage persists through the riverbed gravels after the surface has frozen. When the advancing seasonal frost cuts off the drainage by reaching the permafrost table at some point, hydrostatic pressure develops upstream and water may break through onto the surface at a weak point in the frozen gravels. Seepage through alluvial fans and talus slopes frequently issues in similar icings as well.

2) Subpermafrost Seepages: Perennial springs flowing to the surface along fault or fissure lines, or at karst resurgences, continue to flow through the winter in some places and develop aufeis at their points of issue. The largest icings, some of which are perennial (i.e., there is not time for them to melt away in the summer), are of this sort.

Large springs in the Brooks Range and British Mountains yield water at rates of order 0.1 - 1.0 $m^3 s^{-1}$ and generate very large icings. In the eastern Brooks range about 150 mm of input water per year is required to support the springs (if it is derived locally). Icing volume in the Sagavanirktok River basin is estimated at about $1.2 \times 10^8 m^3$. This would represnet an average ground water discharge of about 6 $m^3 s^{-1}$ over an 8-month winter period, and would add about 23 $m^3 s^{-1}$ to streamflow over a 2-month melt period (data in Williams and van Everdingen, 1973).

The occurrence of groundwater in permafrost regions has been studied in northwestern Canada by Brandon (1965), and is reviewed by Owen(1967). For Alaska, the most recent compilation is by Williams (1970b). Cederstrom (1961) emphasized the exceptional groundwater resource of the Yukon Valley.

Summary

The physical basis for hydrology in northern regions is no different than elsewhere, but the extremely cold thermal conditions lend special character to the hydrological cycle in several respects. Precipitation inputs are effectively redistributed over the year by their persistence as snow for some months. Frozen ground constrains input water to remain on the surface in large degree: the widespread occurrence of muskeg and many lakes stems from this.

The presence of permafrost may influence the usual characteristics of runoff. Storm runoff is usually relatively rapid as the result of the presence of an impermeable substrate at shallow depth. Recession flow may be similarly short-lived or, on tundra heath or muskeg, may be very long. The reasons for this stem from a complex interaction of watershed topography, vegetation cover and ambient evapotranspiration conditions in which the presence of permafrost plays an indirect role of constraining water to remain near the surface. The occurrence of groundwater may be somewhat restricted by the presence of frozen ground, and groundwater flow systems may be modified by the presence of this near impermeable barrier.

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Water Balance Data from Northern Watersheds

Watershed	Location	Area	Surface Cover	Period of Study	Precipitation	Evaporation	Runoff	Reference
Knob Lake drainage basin, Schefferville, Quebec	55°N.,67°W.	35 km^2	Spruce-dwarf birch lichen woodland	56-64	915 mm	280 mm	635 mm	Findlay, 1966
Glenn Creek, nr. Fairbanks, Alaska	65°N.,148°W.	1.8	Spruce-moss and birch-spruce-moss woodland	64-67	313	150[1,8]	150[8]	Dingman, 1971
Putuligayak R., Prudhoe Bay, Alaska	70°N.,148°W.	568	muskeg and heathy tundra	1970	94	27[3]	75	Kane and Carlson, 1973
Small watershed at Point Barrow, Alaska	71°N.,156°W.	1.6	marshy tundra, many ponds	63-66	180	90[8]	90[8]	Brown et.al., 1968
Inugsuin R., eastern Baffin Island	70°N.,70°W.	125	Grass-sedge tundra; investigated at higher elevations	1965	375	-	430	Østrem et.al., 1967
Decade R., eastern Baffin Island	70°N.,70°W.	12.8[5] 7.2[6]	68% glacerized, grass-sedge tundra at low elevations	1965 1965	375 375+86[4]	10[1]	252 450	ibid writer's estimates from data in Østrem et.al., 1967
"[illegible]2" Watershed, Ekalugad Fiord, Baffin Island	69°N.,69°W	2.5	mainly unvegetated;; bedrock and thin drift	1967	616	154[3]	462	writer
Lewis River, central Baffin Island	70°N.,75°W.	208	89% glacierized	63-66	250+300[4]	50[1]	500	Anonymous, 1967
"Weir" R., d'Iberville Fd., Ellesmere Island	81°N.,80°W.	29.4	mainly unvegetated	1973	104 143[7]	~ 0[1]	146 146	Walker, et.al., 1973 writer's estimates from data

1. Computed as the residual of precipitation and runoff measurements.
3. Based on evaporation pan data.
4. Second figure represents net glacial ice ablation.
5. Total watershed area
6. Excludes accumulation zone of the glacier.
7. Precipitation data partially estimated from Eureka data. Writer computed proportional values. Authors directly accepted Eureka data.
8. Estimated partition for long term.

Table 2

Maximum Runoff Rates Cbserved in Northern Rivers

Watershed	Area	Period of Observation	Peak Flow	Runoff/ unit area	Source of runoff	Reference
Idaho Creek, nr. Fairbanks	13.6km^2	1963-67	17.7 $m^3 s^{-1}$	1.31 $m^3 s^{-1} km^{-2}$	Rainstorm	Childers, _et_._al_., 1972
Chatanika R., nr. Fairbanks	625	Aug., '67	555	0.89	Rainstorm	"
Chena River, nr. Fairbanks	3500	Aug., '67	2980	0.85	Rainstorm	"
Koksoak R. N. Quebec	86,000	1962-70	9120	0.116	Snowmelt/rain	CNC/IHD, 1972
R. à la Baleine N. Quebec	29,800	1962-70	3990	0.134	Snowmelt/rain	
George R., N. Quebec	35,200	1962-70	6850	0.195	Snowmelt/rain	CNC/IHD, 1972
"Twisty" Creek, Mackenzie Mtns., N.W.T.	6.55	1972	9.15	1.40	Rainstorm	Sellars, 1973
Arctic Red River, N.W.T.	2,590		3730[1]	1.44[1]	Rainstorm	MacKay _et_ _al_, 1973
Colville River, Alaska	50,000	1962	6100	0.122	Snowmelt	Arnborg _et_ _al_., 1967
Lewis R, Baffin Island	205	1963-66	265	1.29	Rain + ice ablation	Anonymous, 1967
"Jason's" Creek, Devon Island	2.3	1970	1.42	0.61	Snowmelt	McCann, _et_._al_., 1972
Mecham River, Cornwallis Is.,	41.5	1970	26.6	0.64	Snowmelt	"

1. Inferred values. Estimated from observations of runoff at gauging stations on other rivers.

Table 3

Response Characteristics of Northern Rivers

Watershed	Area	Absolute Relief	Surface	Response time	Recession time	Recession constant, t*	Reference
Glenn Creek, nr. Fairbanks	1.8 km^2	237 m	spruce-moss spruce-birch	1 - 2 hrs.		19.6-76.9 hrs. 39 average	Dingman, 1973
"Twisty" Creek, Mackenzie Mtns., N.W.T.	6.55	658	grass, moss, bare slopes	1[1]	8.5 hrs[1]	5.2[1]	Sellars, 1973
Ogotoruk Creek, Alaska	98	84	*Ericphorum*-*Carex* tundra	20[1]	48[1]	43[1]	Likes, 1966
Blow River, Yukon Terr.	3727			18	70[1]		McCloy, 1970
Small drainage basin at Barrow, Alaska	1.6		Marshy tundra, mainly ponds	3 - 10		50-160	Brown, et. el., 1968
Lewis River, Baffin Island	205	735	89% glacier-ized	5[2]			Church, 1972
Decade River, Baffin Island	12.8	1400	68% glacier-ized	5[1]			Østrem, et. al., 1967
"Jason's" Creek, Devon Island	2.3	300	bare	5[3]			McCann and Cogley, 1972
Mecham River, Cornwallis Is.	41.5	200	bare	8 - 9			McCann et. al., 1972
"Weir" River, Elksmere, Is.	29.4	620	bare slopes	~/10			Walker, et. al., 1973

1. Writer's estimate from hydrographs presented in reference.
2. Phase angles of daily runoff peak from local noon during glacier melt runoff.
3. From phase lag of cross correlation between runoff and meteorological properties.

TABLE 4

Classification of Groundwater in Permafrost[1]

Type	Nature of movement	Temperature	Environment
Suprapermafrost			
a) seasonal (freezes in winter)	gravity flow or artesian	alternately < $0^{o}C$ and > $0^{o}C$.	Organic material, alluvium, and other unconsolidated material
b) freezes in part during the winter	gravity flow or artesian	negative	Alluvium and other unconsolidated material.
c) does not freeze in winter	gravity flow	constantly low negative	as above
Intrapermafrost			
a) always liquid	artesian gravity flow	always positive or always negative	Alluvium and unconsolidated materials; rarely in solid rock.
b) always solid (ground ice)	None	always negative	as above
Subpermafrost			
a) shallow	artesian or stationary; at times sealed by permafrost	low positive, or negative if highly mineralized	Alluvium, fissures in bedrock, and karst solution channels
b) deep	artesian or stationary	always positive; may be quite high	In bedrock: aquiferous strata, fissures, and karst solution channels

1. Modified after Tolstikhin (1940) and Muller (1947).

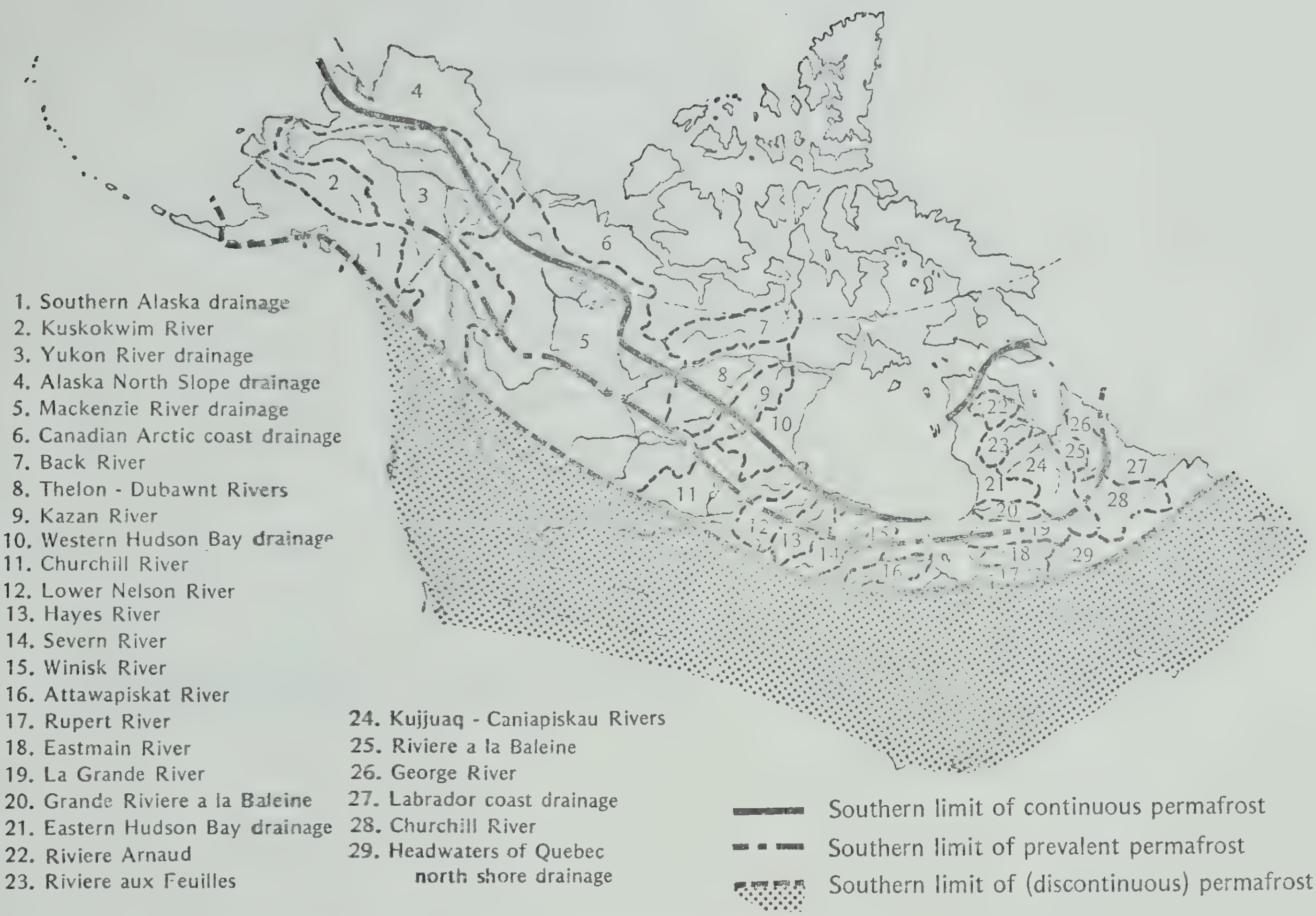

Figure 1. Major drainage basins in northern North America, and generalized limits of the occurrence of permafrost (after Brown).

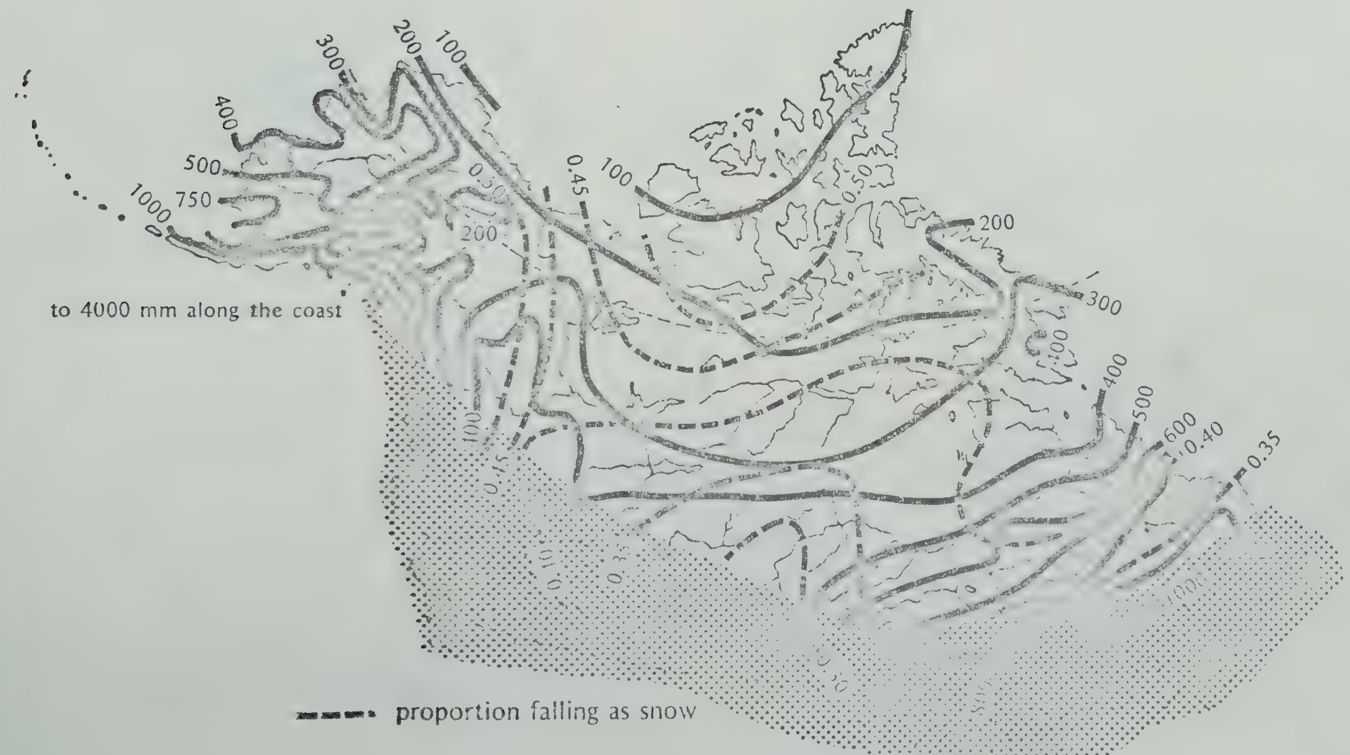

Figure 2. Mean annual precipitation (mm) and proportion falling as snow (from Hare and Hay, 1971; mainly after Met. Service Canada, 1967)

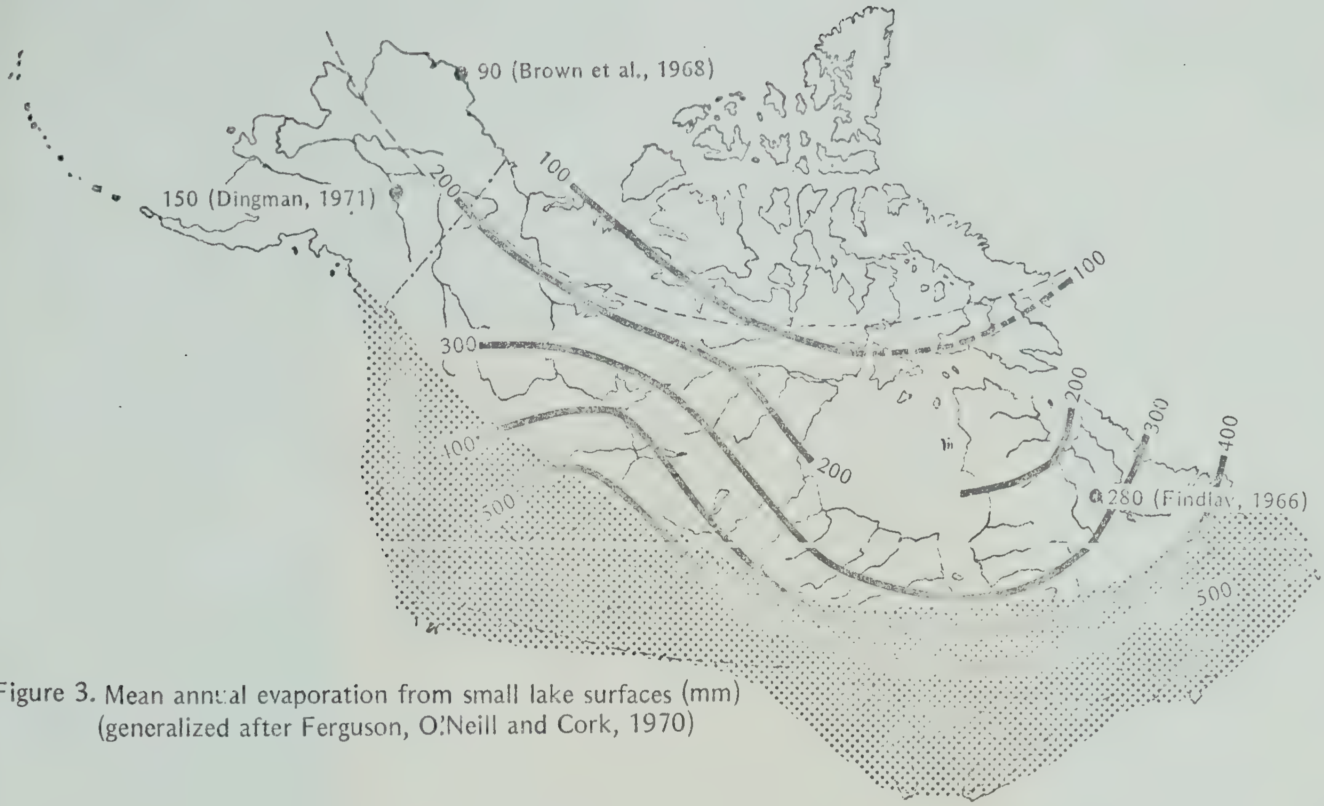

Figure 3. Mean annual evaporation from small lake surfaces (mm) (generalized after Ferguson, O'Neill and Cork, 1970)

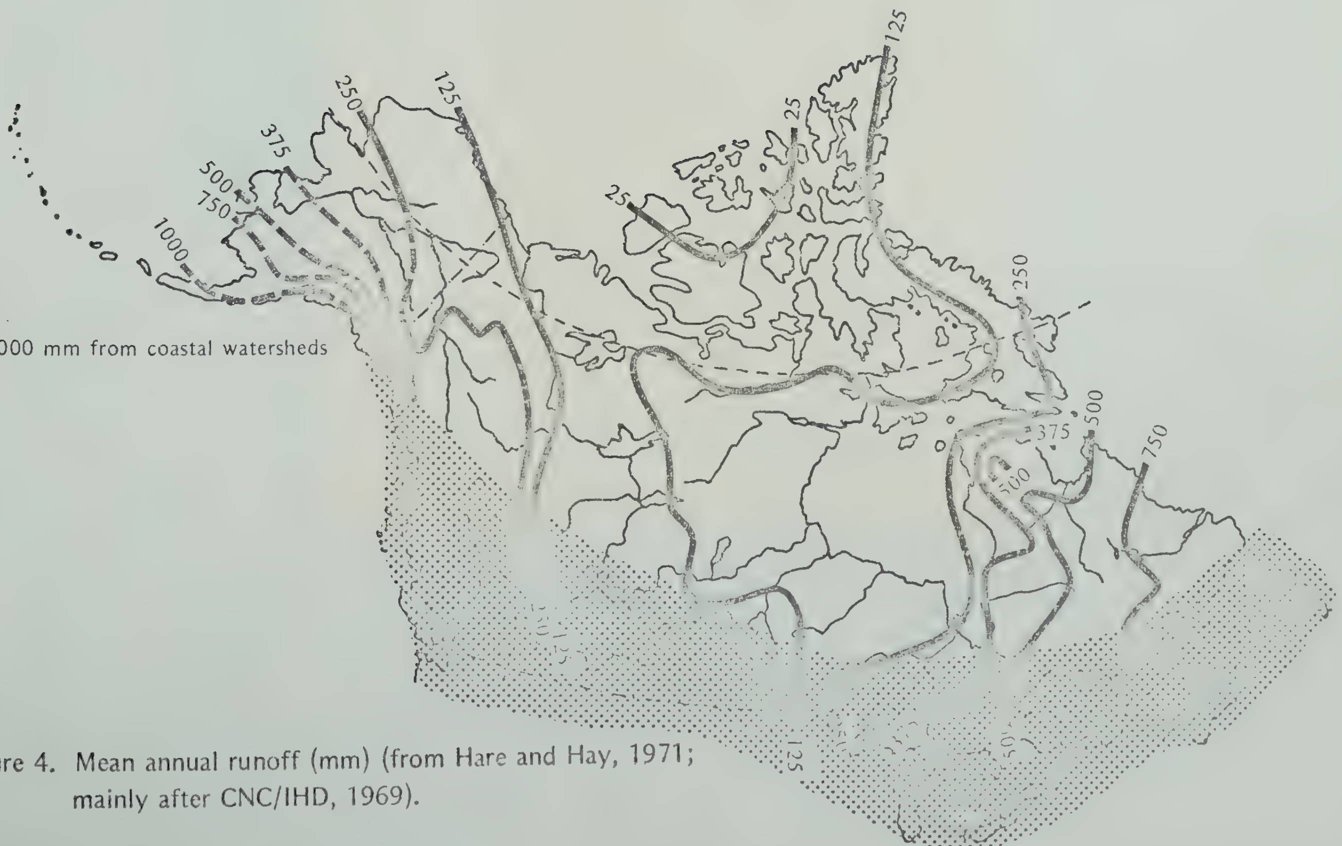

Figure 4. Mean annual runoff (mm) (from Hare and Hay, 1971; mainly after CNC/IHD, 1969).

Michael Cheng

„Hydrologie and Permafrost"

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